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# Relay When Blocked: A Hop-by-Hop mmWave Cooperative Transmission Protocol

Haiyang Ding, *Member, IEEE*, Daniel Benevides da Costa, *Senior Member, IEEE*, Justin Coon, *Senior Member, IEEE*, and Yunfei Chen, *Senior Member, IEEE*

**Abstract**—Obstacles are generally treated as harmful objects for millimeter wave (mmWave) networks due to the directional transmission of mmWave signals and the blockage effects of the obstacles. In this letter, smart antennas are deployed at each blockage to exploit the directivity of the mmWave signal such that the blocked signal at each obstacle can be picked up and forwarded to the destination. Assuming a random Boolean model for the spatially distributed blocking obstacles, the joint distribution of the ordered blockage distances is first characterized, which is then used to develop the exact as well as the asymptotic outage probability conditioned on a given number of blockages. Both theoretical analysis and numerical results show that the proposed protocol achieves full diversity order and can eliminate the error floor caused by the blocking effects, achieving thus superior performance to previous solutions.

**Index Terms**—Blockage, Boolean model, mmWave, relay.

## I. INTRODUCTION

To meet the ever growing demand for wireless traffic, the millimeter wave (mmWave) bands with significant amount of unused bandwidth (20-300GHz) appear to be of great potential for next generation mobile networks. Nonetheless, the propagation characteristics in the mmWave bands are quite different from those of the spectrum below 5 GHz because their diffraction capability is limited and thus, they cannot penetrate through obstacles like buildings, concrete walls, vehicles, and human bodies [1]–[3].

To characterize the effects of obstacles on mmWave propagation, the authors of [4] proposed to use a random Boolean model for the spatially distributed blocking obstacles. Making use of this random Boolean model, Lin *et al.* investigated the fundamental performance of the connectivity of mmWave networks with multi-hop relaying, where intermediate relays are used to route the mmWave signals to turn around obstacles [1]. In [2], the relay nodes were distributed uniformly as a homogeneous Poisson point process (PPP) in order to assist the source node to transmit in the presence of blockages. Very recently, mmWave band was used for wireless power transfer in a tactical network, where network nodes were treated as potential blockages to mmWave signals [3]. It is noteworthy that, in the previous literature, the blockages were treated as harmful objects while relay nodes were pre-scheduled to circumvent these blockages. Different from these previous solutions, in this work we propose to deploy smart antennas at each blockage such that the direction of arrival (DOA) of the incident mmWave signal can be estimated at the blocking obstacle. Then, the “blocked” signal can be picked up and retransmitted toward destination based on the DOA. In this case, a “relay when blocked” mechanism can be implemented

by the obstacles between source and destination. Due to the randomness of the blockages between source and destination, in this work we aim to characterize the effect of blockage (relay) on the transmission performance of mmWave networks. To this end, we first analyze the joint distribution of the ordered blockage distances from the source, and then use it to derive the end-to-end outage probability. Based on the asymptotic outage behavior, the system diversity and array gains are developed, which shows the potential of our proposal to eliminate the error floor phenomenon caused by blocking.

## II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

Consider a source node S that transmits information to a destination D, where we adopt the classical sectored antenna model to capture the use of directional antenna arrays [3], [5]. Specifically, we assume perfect beam alignment between source and destination with the aid of low-rate control network [6] and the directivity gain is thus given by  $a_1 = M_t M_r$ , where  $M_t$  and  $M_r$  denote the main lobe gains of the transmitting and receiving antennas, respectively [5]. In addition, as in [3], we adopt Nakagami- $m$  fading to depict the line-of-sight path such that the probability density function (PDF) of the channel power gain ( $H_l$ ) conforms to the normalized Gamma distribution as below

$$f_{H_l}(x) = \frac{m_0^{m_0} x^{m_0-1}}{\Gamma(m_0)} e^{-m_0 x}, \quad (1)$$

where  $m_0$  denotes the Nakagami- $m$  fading parameter which is generally set to be greater than 2 to denote the line of sight (LOS) [3], and  $x \geq 0$ .

Due to the directional transmission characteristics of mmWave channels, obstacles between source and destination will act as blockages, which are modeled as a simplified Boolean model with fixed shape parameter [3], [4]. In particular, as in [3], we consider a two-dimensional scenario and assume that the blockages between source and destination have a circular cross-section whose diameter is supposed to be  $\beta$ . In addition, the positions of the blockages follow a homogeneous PPP with a density of  $\lambda$ . As a result, the number of blockages between source and destination conforms to a Poisson distribution with mean  $\delta = \lambda d_0 \beta$ , where  $d_0$  denotes the distance between source and destination.

To avoid the blockage, we deploy smart transmitting and receiving antennas at each blockage node. When the mmWave signal is blocked by blockage nodes, we assume that the blockage node is capable of estimating the DOA of the incident mmWave signal and then uses the DOA to aim its beam toward the destination. Since the antenna arrays are deployed in a uniform and circular manner at each blockage, the receiving antenna gain will be the same in all directions (e.g.,  $M_r$ ) [7] such that the receiving node of each hop does not need to perform any beam alignment operations. For example, we may deploy multiple pairs of mmWave transmit/receive antenna arrays on each blockage. The two antenna arrays in one pair are respectively deployed on the opposite sides of each blockage node. Then, if one antenna array in the pair

H. Ding is with School of Information and Communications, National University of Defense Technology, Xi'an, China (e-mail: dinghy2003@hotmail.com).

D. B. da Costa is with Department of Computer Engineering, Federal University of Cear, Sobral, CE, Brazil (email: danielbcosta@ieee.org).

J. Coon is with Department of Engineering Science, University of Oxford (email: justin.coon@eng.ox.ac.uk).

Y. Chen is with School of Engineering, University of Warwick (email: Yunfei.Chen@warwick.ac.uk).

$$\Pr(x_1 \leq d_{(1)} < x_1 + \Delta x_1, x_2 \leq d_{(2)} < x_2 + \Delta x_2, \dots, x_k \leq d_{(k)} < x_k + \Delta x_k | k \text{ blockages}) = \frac{e^{-\lambda\beta x_1} (\lambda\beta \Delta x_1 e^{-\lambda\beta \Delta x_1}) e^{-\lambda\beta(x_2 - x_1 - \Delta x_1)} (\lambda\beta \Delta x_2 e^{-\lambda\beta \Delta x_2}) \dots (\lambda\beta \Delta x_k e^{-\lambda\beta \Delta x_k}) e^{-\lambda\beta(d_0 - x_k - \Delta x_k)}}{\frac{(\lambda\beta d_0)^k}{k!} e^{-\lambda\beta d_0}} = \frac{k!}{d_0^k} \Delta x_1 \Delta x_2 \dots \Delta x_k. \quad (5)$$

detects an incident mmWave signal, the other antenna array in the pair will retransmit<sup>1</sup> the blocked signal toward the destination. In addition, we assume an orthogonal channel access mode such that co-channel interference can be avoided in the considered systems. In this way, if no blockage exists between source and destination, direct transmission is performed and the instantaneous information rate can be expressed as

$$I_D = \log_2 \left( 1 + \frac{P_t a_1 H_0 g(d_0)}{\sigma^2} \right), \quad (2)$$

where  $P_t$  is the transmit power at the source,  $\sigma^2$  denotes the noise variance at the receiving terminal,  $H_0$  represents the channel power gain as defined before and,  $g(d_0) \triangleq C_0 \min[1, d_0^{-\alpha}]$  represents the path loss with  $C_0$  and  $\alpha$  being the path loss intercept and path loss exponent, respectively.

When one or multiple blockages exist between source and destination, the information can be relayed by the blockages in a hop-by-hop manner such that the end-to-end instantaneous information rate can be written as

$$I_{(k+1)\text{-hop}} = \frac{1}{k+1} \log_2 \left( 1 + \frac{P_t a_1}{\sigma^2} \min [H_{SR_1} g(d_{(1)}), H_{R_1 R_2} g(d_{(2)} - d_{(1)}), \dots, H_{R_{k-1} R_k} g(d_{(k)} - d_{(k-1)}), H_{R_k D} g(d_0 - d_{(k)})] \right), \quad (3)$$

where  $k \geq 1$  is the number of blockages,  $H_{R_{k-1} R_k}$  is the channel power gain between the  $(k-1)$ -th blockage and the  $k$ -th one,  $d_{(k)}$  denotes the distance between the source and the  $k$ -th blockage, satisfying to  $0 \leq d_{(1)} \leq \dots \leq d_{(k)} \leq d_0$ .

### III. OUTAGE ANALYSIS

In this section, we investigate the outage performance of the considered mmWave system. The outage event happens when the instantaneous information rate falls below a pre-defined rate threshold  $\Omega_0$  bit/s/Hz. To proceed, we first determine the joint distribution of  $\{d_{(1)}, d_{(2)}, \dots, d_{(k)}\}$ , which is summarized below.

**Lemma 1:** The joint PDF of the ordered distance variables  $\{d_{(1)}, d_{(2)}, \dots, d_{(k)} | d_{(1)} \leq d_{(2)} \leq \dots \leq d_{(k)}\}$ , conditioned on the event that there are  $k$  blockages between source and destination, is given by

$$f_{d_{(1)}, d_{(2)}, \dots, d_{(k)}}(x_1, x_2, \dots, x_k | k \text{ blockages}) = \frac{k!}{d_0^k}, \quad (4)$$

in which  $0 \leq x_1 \leq x_2 \leq \dots \leq x_k \leq d_0$ .

*Proof:* Suppose that the  $n$ -th blockage is located within the interval  $x_n \leq d_{(n)} < x_n + \Delta x_n$  and the intervals  $\Delta x_n$  ( $n = 1, 2, \dots, k$ ) are sufficiently small such that there is no superposition among different intervals, then we have (5), shown at the top of this page. Now, by letting  $\Delta x_n$  ( $n = 1, \dots, k$ ) approach to 0, we can arrive at (4), which completes the proof. ■

Next, we first focus on the case of no blockage.

#### A. No blockage: Direct transmission

The outage probability for direct transmission can be formulated as

$$P_{\text{out}}^{\text{LOS}} = e^{-\delta} \Pr \left( H_0 < \frac{\tau_0 \sigma^2}{a_1 P_t g(d_0)} \right) = \frac{e^{-\delta}}{\Gamma(m_0)} \gamma \left( m_0, \frac{m_0 \tau_0 \sigma^2}{a_1 P_t g(d_0)} \right), \quad (6)$$

where  $\tau_0 \triangleq 2^{\Omega_0} - 1$  is the signal-to-noise ratio (SNR) threshold,  $\gamma(\cdot, \cdot)$  is the lower incomplete Gamma function [9, Eq. (8.350.1)] and the last step is owing to [9, Eq. (3.381.1)]. When the transmit SNR  $P_t/\sigma^2$  is large, we have  $\gamma(\alpha, x) \simeq x^\alpha/\alpha$  [9, Eq. (8.354.1)] such that (6) can be asymptotically expressed as

$$P_{\text{out}}^{\text{LOS}} \simeq \frac{e^{-\delta} \left( \frac{m_0 \tau_0 \sigma^2}{a_1 P_t g(d_0)} \right)^{m_0}}{\Gamma(m_0 + 1)}, \quad (7)$$

from which it can be observed that the system diversity gain is  $m_0$  for the case of direct transmission.

#### B. Multiple blockages: Multi-hop relaying

For the scenarios where there is one or multiple blockages lying between source and destination, multi-hop relaying is carried out by blockages in a hop-by-hop manner from source to destination. The following proposition presents a general outage expression for the case of multiple blockages.

**Proposition 1:** When there are  $k$  blockages between source and destination, the system outage probability can be expressed as

$$P_{\text{out}}^{k\text{-blockage}} = \frac{(\lambda\beta d_0)^k}{k!} e^{-\lambda\beta d_0} \times \left[ 1 - \int_0^{d_0} \int_{d_{(1)}}^{d_0} \int_{d_{(2)}}^{d_0} \dots \int_{d_{(k-1)}}^{d_0} \frac{k!}{d_0^k} \frac{\prod_{l=1}^{k+1} \Gamma \left( m_0, \frac{m_0 \hat{\tau}_k}{g(d_{(l)} - d_{(l-1)})} \right)}{[\Gamma(m_0)]^{k+1}} dd_{(1)} \dots dd_{(k)} \right], \quad (8)$$

where  $\hat{\tau}_k \triangleq \frac{\sigma^2 \tau_k}{a_1 P_t}$ ,  $\tau_k = 2^{(k+1)\Omega_0} - 1$ ,  $\Gamma(\cdot, \cdot)$  denotes the upper incomplete Gamma function [9, Eq. (8.350.2)],  $d_{(0)} = 0$  and  $d_{(k+1)} = d_0$ . In the high SNR regime<sup>2</sup>, the asymptotic expression is obtained from (8) as

$$P_{\text{out}}^{k\text{-blockage}} \simeq (\lambda\beta)^k e^{-\lambda\beta d_0} \frac{m_0^{m_0-1} (\hat{\tau}_k)^{m_0}}{\Gamma(m_0)} \int_0^{d_0} \int_{d_{(1)}}^{d_0} \int_{d_{(2)}}^{d_0} \dots \int_{d_{(k-1)}}^{d_0} \left( \sum_{l=1}^{k+1} \frac{1}{[g(d_{(l)} - d_{(l-1)})]^{m_0}} \right) dd_{(1)} \dots dd_{(k)}. \quad (9)$$

<sup>2</sup>According to [3], [10], [11], the typical transmit power is 30 ~ 33 dBm, and the typical noise power is -71 dBm for a bandwidth of 2 GHz and a noise figure of 10. As a result, the transmit SNR will be larger than 100 dB for typical mmWave systems.

<sup>1</sup>In this work, we adopt decode-and-forward relaying mode at the blockages, which can eliminate noise accumulation and is more appropriate for multi-hop relaying in comparison with amplify-and-forward mode [8].

*Proof:* Knowing that outage will not occur only when none of the hops between source and destination is in outage status, (8) can be developed with the aid of Lemma 1, whereas (9) is achieved by utilizing  $\Gamma(m_0, m_0 x) \simeq \Gamma(m_0) \left[1 - \frac{m_0^{m_0-1}}{\Gamma(m_0)} x^{m_0}\right]$  for  $x \rightarrow 0$ . ■

*Corollary 1:* When there are  $k$  blockages between source and destination, the achievable diversity order is  $m_0$ , and the array gain can be written as

$$G_a^{k\text{-blockage}} = \frac{a_1(\lambda\beta)^{-\frac{k}{m_0}} e^{\frac{\lambda\beta d_0}{m_0}} m_0^{-\frac{m_0-1}{m_0}} \theta_k^{-\frac{1}{m_0}}}{\tau_k[\Gamma(m_0)]^{-\frac{1}{m_0}}}, \quad (10)$$

where  $\theta_k$  is given by

$$\theta_k = \sum_{l=1}^{k+1} \int_0^{d_0} \int_{d_{(1)}}^{d_0} \int_{d_{(2)}}^{d_0} \cdots \int_{d_{(k-1)}}^{d_0} \frac{1}{[g(d_{(l)} - d_{(l-1)})]^{m_0}} dd_{(1)} dd_{(2)} \dots dd_{(k)}. \quad (11)$$

*Proof:* According to the definition of diversity and array gain [12], one can arrive at (10) based on (9). ■

*Corollary 2:* As  $\lambda \rightarrow \infty$ , a closed-form expression of (10) can be expressed as

$$G_a^{k\text{-blockage}} \simeq \frac{C_0 a_1 (\lambda\beta d_0)^{-\frac{k}{m_0}} e^{\frac{\lambda\beta d_0}{m_0}} m_0^{-\frac{m_0-1}{m_0}} (k+1)^{-\frac{1}{m_0}}}{\tau_k[\Gamma(k+1)\Gamma(m_0)]^{-\frac{1}{m_0}}}. \quad (12)$$

*Proof:* As  $\lambda$  goes to infinity,  $g(d_{(l)} - d_{(l-1)})$  tends to be  $C_0$  such that one can attain  $\theta_k = (k+1)C_0^{-m_0} d_0^k / k!$  by induction. Then, by substituting  $\theta_k$  into (10) and after some algebraic manipulations, we can attain (12). ■

For the special cases of one blockage or two blockages, we can arrive at the following simplified expressions without multifold integrals. For  $k=1$ , by averaging over the PDF of the ordered blockage distances and invoking [9, Eqs. (8.352.4) and (3.381.1)], one can attain

$$P_{\text{out}}^{1\text{-blockage}} = \delta e^{-\delta} - \frac{\delta e^{-\delta}}{d_0[\Gamma(m_0)]^2} \xi, \quad (13)$$

where  $\xi$  is given by

$$\begin{aligned} \xi|_{d_0 \geq 2} &= \frac{2\Gamma\left(m_0, \frac{m_0 \hat{\tau}_1}{C_0}\right) \Gamma(m_0)}{\alpha} \left(\frac{m_0 \hat{\tau}_1}{C_0}\right)^{-\frac{1}{\alpha}} \sum_{k=0}^{m_0-1} \frac{1}{k!} \\ &\times \left[ \gamma\left(k + \frac{1}{\alpha}, \frac{d_0^\alpha m_0 \hat{\tau}_1}{C_0}\right) - \gamma\left(k + \frac{1}{\alpha}, \frac{(d_0-1)^\alpha m_0 \hat{\tau}_1}{C_0}\right) \right] \\ &+ [\Gamma(m_0)]^2 \sum_{k_1=0}^{m_0-1} \sum_{k_2=0}^{m_0-1} \frac{\left(\frac{m_0 \hat{\tau}_1}{C_0}\right)^{k_1+k_2}}{k_1! k_2!} \\ &\times \int_1^{d_0-1} r^{\alpha k_1} (d_0 - r)^{\alpha k_2} e^{-\frac{m_0 \hat{\tau}_1}{C_0} r^\alpha - \frac{m_0 \hat{\tau}_1}{C_0} (d_0-r)^\alpha} dr, \quad (14a) \end{aligned}$$

$$\begin{aligned} \xi|_{1 \leq d_0 < 2} &= \frac{2\Gamma\left(m_0, \frac{m_0 \hat{\tau}_1}{C_0}\right) \Gamma(m_0)}{\alpha} \left(\frac{m_0 \hat{\tau}_1}{C_0}\right)^{-\frac{1}{\alpha}} \\ &\times \sum_{k=0}^{m_0-1} \frac{1}{k!} \left[ \gamma\left(k + \frac{1}{\alpha}, \frac{d_0^\alpha m_0 \hat{\tau}_1}{C_0}\right) - \gamma\left(k + \frac{1}{\alpha}, \frac{m_0 \hat{\tau}_1}{C_0}\right) \right] \\ &+ (2 - d_0) \left[ \Gamma\left(m_0, \frac{m_0 \hat{\tau}_1}{C_0}\right) \right]^2, \quad (14b) \end{aligned}$$

$$\xi|_{0 \leq d_0 < 1} = d_0 \left[ \Gamma\left(m_0, \frac{m_0 \hat{\tau}_1}{C_0}\right) \right]^2. \quad (14c)$$

In the high transmit SNR regime, by utilizing  $\Gamma(m_0, m_0 x) \simeq \Gamma(m_0) \left[1 - \frac{m_0^{m_0-1}}{\Gamma(m_0)} x^{m_0}\right]$ ,  $\gamma(\alpha, x) \simeq \frac{x^\alpha}{\alpha}$  for  $x \rightarrow 0$ , and after some algebraic arrangements, the system outage probability can be asymptotically expressed as

$$P_{\text{out}}^{1\text{-blockage}} \simeq \begin{cases} \frac{2\delta e^{-\delta} m_0^{m_0-1}}{\Gamma(m_0)} \left(\frac{\hat{\tau}_1}{C_0}\right)^{m_0} \\ \times \left[ \frac{1}{d_0} \left( \frac{\alpha m_0 + d_0^{\alpha m_0+1}}{\alpha m_0 + 1} \right) \right], & \text{if } d_0 \geq 1, \\ \frac{2\delta e^{-\delta} m_0^{m_0-1}}{\Gamma(m_0)} \left(\frac{\hat{\tau}_1}{C_0}\right)^{m_0}, & \text{if } 0 \leq d_0 < 1. \end{cases} \quad (15)$$

It can be readily checked that for  $d_0 \geq 1$ , the multiplicative factor  $\frac{1}{d_0} \left( \frac{\alpha m_0 + d_0^{\alpha m_0+1}}{\alpha m_0 + 1} \right)$  is an increasing function and no less than 1. This means that on the basis of the benchmark form  $\frac{2\delta e^{-\delta} m_0^{m_0-1}}{\Gamma(m_0)} \left(\frac{\hat{\tau}_1}{C_0}\right)^{m_0}$ , a penalty factor  $\frac{1}{d_0} \left( \frac{\alpha m_0 + d_0^{\alpha m_0+1}}{\alpha m_0 + 1} \right) \geq 1$  will affect the asymptotic outage performance for the distance range  $d_0 \geq 1$ . For the case  $k=2$ , we can arrive at a closed-form asymptotic expression for (9) as below

$$P_{\text{out}}^{2\text{-blockage}} \simeq \begin{cases} \frac{3d_0^2 (\hat{\tau}_2)^{m_0} m_0^{m_0-1} (\lambda\beta)^2}{2C_0^{m_0} \Gamma(m_0)} e^{-\lambda\beta d_0}, & \text{if } 0 < d_0 \leq 1, \\ \frac{(\hat{\tau}_2)^{m_0} m_0^{m_0-1} (\lambda\beta)^2}{\Gamma(m_0)} e^{-\lambda\beta d_0} \chi, & \text{if } d_0 > 1, \end{cases} \quad (16)$$

where  $\chi$  is given by

$$\begin{aligned} \chi &= \frac{d_0 + 0.5}{C_0^{m_0}} + \frac{1}{C_0^{m_0}} \left[ \frac{d_0 (d_0^{\alpha m_0+1} - 1)}{\alpha m_0 + 1} - \frac{d_0^{\alpha m_0+2} - 1}{\alpha m_0 + 2} + \right. \\ &\left. + \frac{2\alpha m_0 (d_0 - 1)}{\alpha m_0 + 1} + \frac{2(d_0^{\alpha m_0+2} - 1)}{(\alpha m_0 + 1)(\alpha m_0 + 2)} \right]. \quad (17) \end{aligned}$$

Similar to (15), the penalty factor for (16) becomes  $\frac{2C_0^{m_0} \chi}{3d_0^2} \geq 1$  for  $d_0 \geq 1$ .

### C. Overall outage probability

*Proposition 2:* The overall outage probability of the proposed relay-when-blocked protocol can be expressed as

$$P_{\text{out}} = P_{\text{out}}^{\text{LOS}} + \sum_{k=1}^{\infty} P_{\text{out}}^{k\text{-blockage}}, \quad (18)$$

where the exact outage probability can be attained by replacing  $P_{\text{out}}^{\text{LOS}}$  and  $P_{\text{out}}^{k\text{-blockage}}$  with (6) and (8), respectively, whereas the asymptotic one can be achieved by using (7) and (9).

*Corollary 3:* The achievable diversity order of the proposed “relay when blocked” protocol is  $m_0$ , whereas the overall array gain is related to the individual one for each possible blockage case in a harmonic form as

$$G_a = \left[ \lim_{N \rightarrow \infty} \frac{1}{N} H \left( (G_a^{\text{LOS}})^{m_0}, (G_a^{1\text{-blockage}})^{m_0}, \dots, (G_a^{(N-1)\text{-blockage}})^{m_0} \right) \right]^{\frac{1}{m_0}}, \quad (19)$$

where  $H(\cdot)$  denotes the harmonic mean function, and  $G_a^{\text{LOS}} = \frac{a_1 g(d_0)}{m_0 \tau_0} e^{\frac{\delta}{m_0}} [\Gamma(m_0 + 1)]^{\frac{1}{m_0}}$ , as shown by (7).



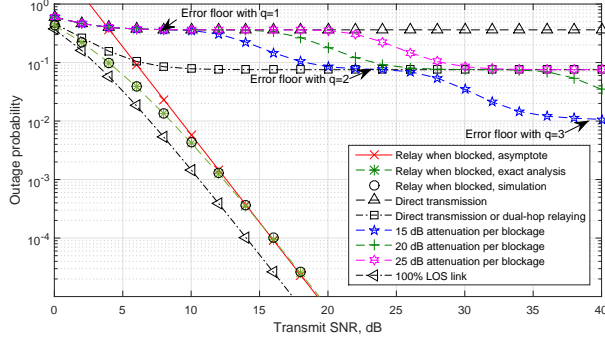


Fig. 1: Comparison of different protocols in terms of outage probability ( $\lambda = 0.05$ ).

#### IV. NUMERICAL RESULTS AND DISCUSSION

In this section, without loss of generality, the path loss intercept  $C_0$  is set to  $\left(\frac{4\pi f_c}{v}\right)^2$ , where  $v = 3 \times 10^8 \text{ ms}^{-1}$  and  $f_c = 28 \text{ GHz}$ . In addition, the main lobe antenna gain is set to  $M_t = M_r = 15 \text{ dB}$ . Similar to [3], we consider circular blockages with diameter  $\beta = 0.9 \text{ m}$ . Unless otherwise specified, we assume  $d_0 = 10 \text{ m}$ ,  $\alpha = 3$ ,  $m_0 = 3$ , and  $\Omega_0 = 1$ .

Fig. 1 compares the outage performance of the proposed “relay when blocked” protocol along with three other benchmark protocols. The first one is direct transmission which permits information transmission only when no blockage exists between source and destination. The second one is the direct transmission plus dual-hop relaying protocol, which allows information transmission when no blockage or at most one blockage exists between source and destination. The third one assumes that each blockage merely incurs a severe path attenuation [13]. Assuming that each blockage incurs an additional  $A_L$  dB attenuation relative to LOS path between source and destination, it follows from (6) that the outage probability of the third benchmark protocol is given by

$$P_{\text{out}}^{A_L \text{ loss per blockage}} = \sum_{k=0}^{\infty} \frac{\delta^k e^{-\delta}}{k!} \frac{\gamma\left(m_0, \frac{m_0 \tau_0 \sigma^2 10^{\frac{k A_L}{10}}}{a_1 P_t g(d_0)}\right)}{\Gamma(m_0)}. \quad (20)$$

From the figure, it is clear that all of the three benchmark protocols have error floors, which can be readily determined to be  $1 - e^{-\delta}$  and  $1 - e^{-\delta} - \delta e^{-\delta}$  for the first two ones. Accordingly, the  $q$ -th ( $q \geq 1$ ) error floor can be determined as  $\sum_{k=q}^{\infty} \frac{\delta^k e^{-\delta}}{k!} \gamma\left(m_0, \frac{m_0 \tau_0 \sigma^2 10^{\frac{k A_L}{10}}}{a_1 P_t g(d_0)}\right) / \Gamma(m_0)$ , because with an increase in the transmit SNR  $P_t / \sigma^2$ , the terms with  $k = 0, 1, \dots, q-1$  become infinitesimal and thus can be neglected in evaluating (20). As thus, a “going downstairs” behavior with multiple error floors is observed for the penetration loss model. In contrast, by exploiting the blockages as relay nodes, the proposed protocol eliminates the error floor such that the outage performance improves with the transmit SNR. Besides, it can be seen that the outage curve with 100% LOS link is very close to the counterpart of the proposed “relay when blocked” scheme. When  $\lambda$  decreases, their performance gap will reduce further since the probability of LOS link, i.e.,  $e^{-\lambda d_0 \beta}$ , will approach 1. From Figure 2, it is observed that with an increase in the blockage density and/or the size of blockage, the outage probability increases monotonically.

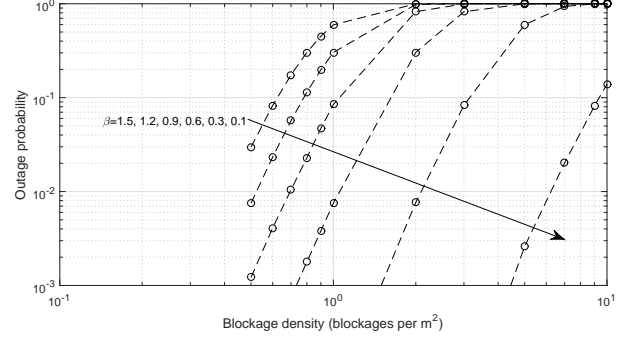


Fig. 2: Effects of blockage density and size on outage probability ( $P_t / \sigma^2 = 25 \text{ dB}$ ).

#### V. CONCLUDING REMARKS

In this letter, making use of the directivity of the incident mmWave signal, we have presented a “relay when blocked” mechanism to tackle the blocking effects in mmWave transmissions. The proposed scheme has eliminated the error floor caused by the blocking effects. In addition, it has been shown that the overall array gain of the proposed scheme is a function of the harmonic mean of the individual array gain for each possible blockage case. Under non-homogeneous fading scenarios, it follows from Proposition 1 and Corollary 1 that the diversity order for the case of  $k$  blockages ( $k \geq 1$ ) is

$$\hat{G}_d^{k\text{-blockage}} = \min[m_1, m_2, \dots, m_{k+1}] \triangleq m_{(k)}^*, \quad (21)$$

where  $m_l$  denotes the fading parameter of the  $l$ -th hop. By its turn, the overall diversity order can be achieved as

$$\hat{G}_d = \lim_{k \rightarrow \infty} \min[m_0, m_{(1)}^*, m_{(2)}^*, \dots, m_{(k)}^*], \quad (22)$$

in which  $m_{(k)}^*$  is defined as in (21).

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